



Compression After Impact Strength Comparison of Rohacell Foam and Aluminum Honeycomb Core Sandwich Structure

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LIST OF ACRONYMS

ATL	automatic tape laying
BVID	barely visible impact damage
CAI	compression after impact
MSFC	Marshall Space Flight Center
PAF	payload adapter fitting

NOMENCLATURE

L	core ribbon
t_{\max}	maximum thickness between cell walls
t_{\min}	minimum thickness between cell walls

TECHNICAL MEMORANDUM

COMPRESSION AFTER IMPACT STRENGTH COMPARISON OF ROHACELL FOAM AND ALUMINUM HONEYCOMB CORE SANDWICH STRUCTURE

1. INTRODUCTION

As part of NASA's SLS program, the damage tolerance of sandwich structure for a payload adapter fitting (PAF) is being assessed. A previous study¹ examined the compression after impact (CAI) strength of foam and honeycomb core sandwich structure with barely visible impact damage (BVID), however, the CAI strength at impact energy levels other than BVID may be of interest, especially since what constitutes BVID is so subjective. By testing across a wider range of impact severity levels, if the definition of BVID is changed later in the program, then little or no extra data will need to be generated. Also, by using the same impact energy levels, a direct comparison of the damage tolerance characteristics of foam core versus aluminum honeycomb core can be made. This study assessed the CAI strength of foam and honeycomb core sandwich structure with impact energies between 2 and 8 ft•lb. The sandwich structures in this study were the same as those in the previous study¹ with the exception that specimens with an outer layer of fabric were not tested in this study. For the aluminum honeycomb sandwich structure, the specimens were tested with the ribbon direction of the core both parallel and perpendicular to the direction of loading to ascertain if there was any difference in CAI strength results (and thus influence of the core due to its orientation to the direction of loading).

In the previous study,¹ it was found that the Rohacell® foam and aluminum honeycomb core specimens fail in compression by different mechanisms for the core densities used in that study. The low shear modulus of the foam core produced core shear buckling failures in which the face sheets stayed mostly intact. The honeycomb specimens failed by face sheet failure. Despite the differing failure mechanisms, the type of core appeared not to have had a significant effect on CAI strength (when compared on a weight basis) at the levels of BVID chosen for that study when comparing a 1-in-thick honeycomb core to a 0.5-in-thick foam core. However, if a 0.5-in-thick honeycomb core had been used, the CAI strength results, when compared on a weight bases, would be expected to be significantly higher (due to a lower weight since there is less honeycomb); however, a lower buckling load could be expected. Unfortunately, 0.5-in-thick aluminum honeycomb of the same density as the 1-in-thick aluminum honeycomb was not available to test this hypothesis.

2. MATERIALS AND SPECIMENS

The face sheets of the sandwich specimens tested in this study consisted of Hexcel® IM7 carbon fiber with Hexcel 8552-1 epoxy resin which were co-cured to the core. All the face sheets were manufactured by automatic tape laying (ATL) at NASA MSFC (Marshall Space Flight Center). The layup for the face sheets was 8-ply $[-45/0/+45/90]_s$ quasi-isotropic. The honeycomb sandwich structure was manufactured with the core ribbon (L') direction aligning with the 90° fiber direction. The sandwich structure had a layer of FM®300–2M epoxy film adhesive placed over the core material prior to the automated tape laying process used to manufacture the face sheets. Two types of core that have been included in some of the design configurations of the PAF were tested in this study: aluminum honeycomb with a density of 4.0 lb/ft^3 and a thickness of 1.0 inches and Rohacell Hero 71 Polymethacrylimide (PMI) foam core with a density of 4.7 lb/ft^3 and a thickness of 0.5 inches. The compressive and shear properties of the two types of core (as given by vendor data) are compared in table 1. A cutaway schematic of the cross-section of the honeycomb core sandwich structure used in this damage tolerance study showing the lay-up of the face sheet and the direction of the core is shown in figure 1. The foam core sandwich structure had an identical face sheet layup.

Table 1. Select properties of the core materials used in this study.

	Compression Strength (psi)	Compression Modulus (ksi)	Shear Strength (psi)	Shear Modulus (ksi)
4.5 lb/ft ³ AL Honeycomb	690	150	L-Direction: 340 W-Direction: 220	L-Direction: 70 W-Direction: 31
4.7 lb/ft ³ PMI Foam	160	7.0	189	4.1

As can be seen from table 1, the foam core has much lower strength and stiffness properties. The foam core was considered for use on the PAF structure, despite these lower properties, since the foam core could more easily be formed to fit the curvature of the PAF and was also more readily available than the aluminum honeycomb core.

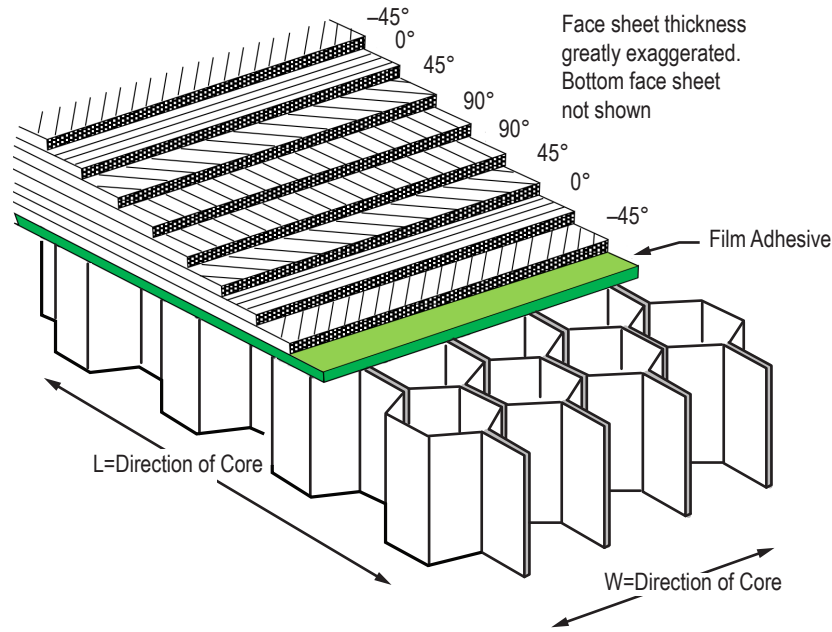


Figure 1. Cross-sectional schematic of honeycomb sandwich structure used in this study.

The sandwich structure was cured in an autoclave with a pressure of 40 psi and a temperature of 350 °F. The two flat sandwich panels made for use in this damage tolerance study (one panel with aluminum honeycomb core and one panel with Rohacell foam core) were 36 inches × 36 inches in size. The sandwich structure showed good consolidation, and typical fiber waviness of the face sheets on the honeycomb core panels was noted as in the cross-sectional photomicrographs (cut in the 0°-direction) of the two types of specimens as shown in figure 2. The thickness values of the face sheets on the honeycomb panels varied from a minimum at the cell walls (t_{\min}) to a maximum between the cell walls (t_{\max}) as noted in figure 2. A nominal value for the face sheet thickness can be used based on the average of numerous random thickness measurements.

Using photomicroscopy and measuring tools contained within the software attached to the microscope, the nominal face sheet thicknesses of the two types of specimens tested were measured and are included in table 2. Note that the honeycomb core sandwich specimens had a lower measured face sheet thickness value than the equivalent face sheet on the foam core sandwich structure. This is due to the localized high compaction pressure that the cell walls of the honeycomb induce on the face sheet during cure causing ‘thin spots’ that have a high fiber volume fraction and skew the average thickness to a lower value.

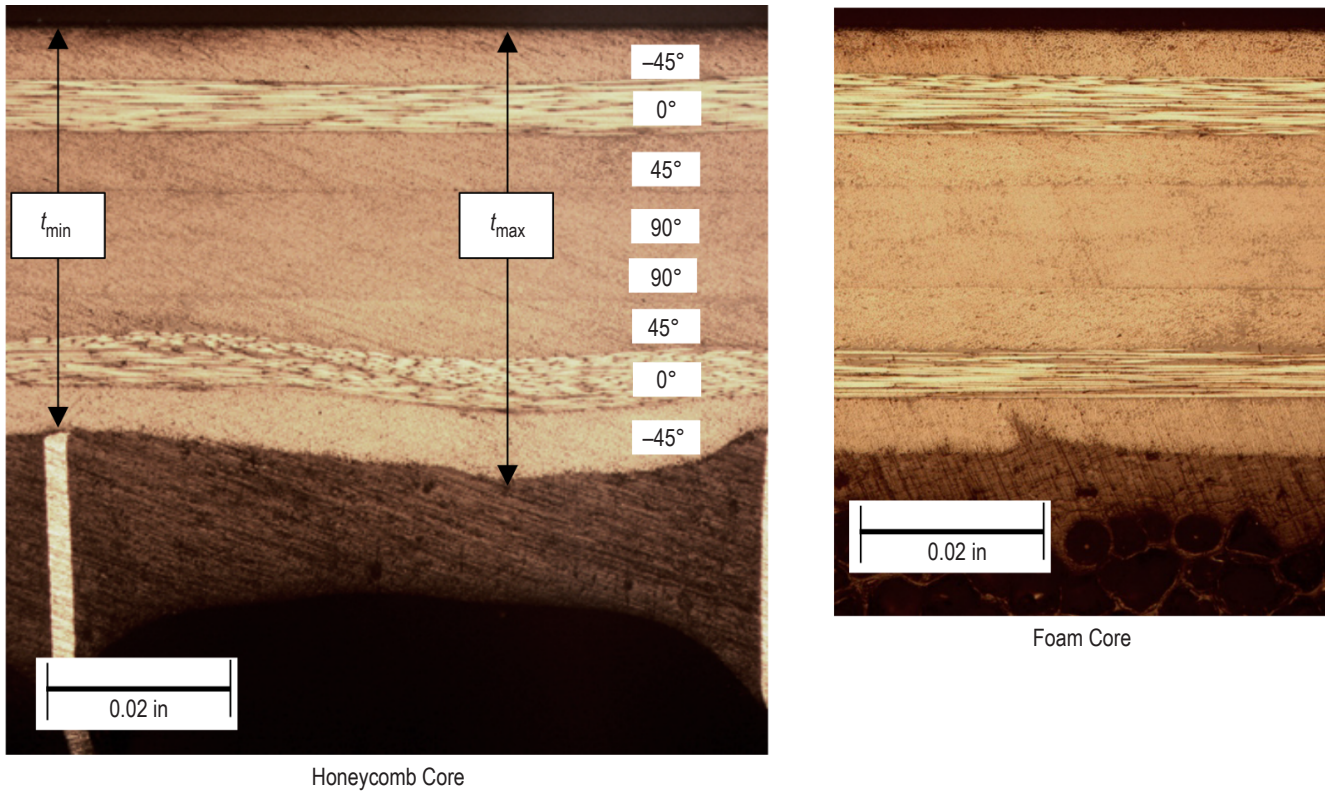


Figure 2. Cross section photomicrographs showing face sheet waviness of inner plies (plies closest to the core) on honeycomb core specimens (left picture) and no waviness of plies on foam core specimens (right picture).

The areal weight (weight per unit surface area) of each of these sandwich structures was measured, and the results are presented in table 2. Note that the units of weight are in ‘pound mass’ (lbm) to avoid confusion with load applied to the specimen by the load frame which is measured in ‘pounds of force’ (lbf). Since the honeycomb core is twice as thick as the thickness of the foam core, to obtain a better comparison on a weight basis between foam core and honeycomb core specimens, the calculated areal weight of honeycomb core specimens with a 0.5-inch thickness are also included. These values were calculated based on the measurements from the 1-in-thick honeycomb core and the core having a density of 4.5 lb/ft³. For the damage tolerance aspects of the sandwich structure in this study, the validity of this comparison is contingent upon the honeycomb core specimens failing by face sheet failure during CAI testing for both the 1-in thickness core and the 0.5-in thickness core. Since face sheet failure was the failure mode (as will be seen later in the results section), it was assumed that the 0.5-in honeycomb core would fail in the same manner although this was not proven in this study.

The two large sandwich panels were cut into 6-in-tall (direction of loading) by 4-in-wide specimens using a diamond saw. The top and bottom edges of these specimens were then machined to ≈ 0.001 inches tolerance of parallelism using a vertical end mill with a solid carbide cutting tool (Onsrud 67–526 designed for carbon fiber machining). The side edges of the specimens were machined to be perpendicular to the top and bottom edges.

Table 2. Areal weight of the specimens used in this study.

Sandwich Structure Type	Nominal Face Sheet Thickness (in)	Areal Weight (lbm/in ²) Core Thickness	
		1.0-in	0.5-in
Foam Core	0.059	N/A	0.0086
Honeycomb Core	0.049	0.0100	0.0074*

*Calculated, value, not directly measured.

Undamaged strength testing of the honeycomb sandwich structure was not pursued in this study since the undamaged specimens exhibited end-brooming, which is not a valid failure mode. This study concerns damage tolerance testing and undamaged strength values are not relevant.

3. IMPACT DAMAGE TESTING

An instrumented drop weight impact tower was used to impart impact damage to the sandwich specimens. The impactor had a 0.5-in-diameter tip. A picture of the impact tester used is shown in figure 3. The selected impact energies were 2.0, 3.1, 4.5, and 8 ft•lb. Results of the impact tests showing the maximum load of the impact event and the dent depth formed on the specimen are summarized in table 3. The dent measurements were taken at least 24 hr after impact to allow for any ‘relaxation’ of the dent depth.

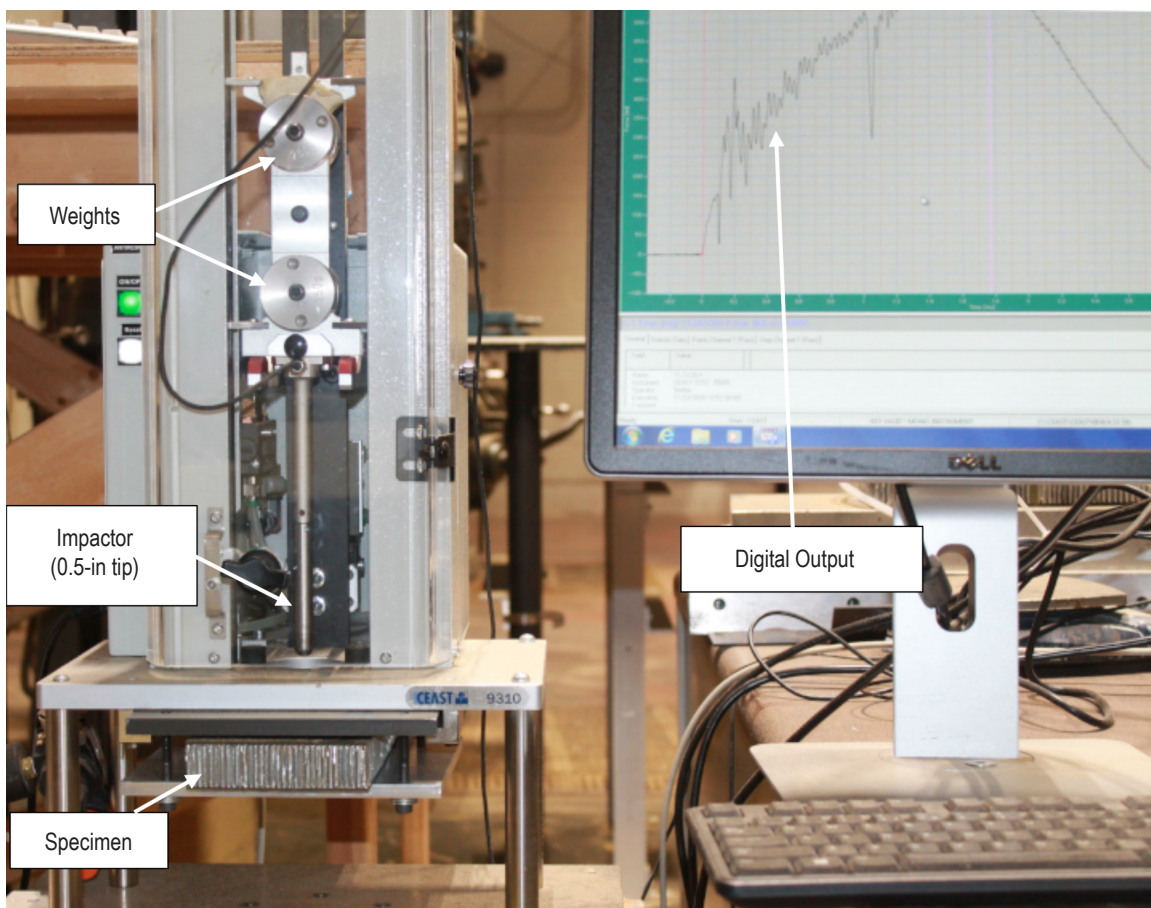


Figure 3. Photograph of instrumented impactor used in this study.

Table 3. Summary of results from impact testing.

Configuration	Impact Energy (ft-lbs)	Specimens Tested	Maximum Load of Impact (lbs)	Dent Depth (mils)
Foam Core	2.0	5	527±10	3.5±0.5
	3.1	3	652±15	3.3±0.6
	4.5	3	765±19	10.5±1.3
	8.0	3	809±18	25.8±1.3
Honeycomb Core	2.0	3	556±33	9.8±1.2
	3.1	3	707±5	15.0±1.0
	4.5	3	839±10	24.3±5.5
	8.0	3	820±75	54.7±3.3

Note that for a given impact energy level, the dent depth is significantly larger on the aluminum honeycomb specimens.

A sample of visual damage produced by each of the various levels of impact energy are shown in figure 4. The specimens are presented in pairs according to the impact energy with the foam core specimens on the left and the honeycomb core specimens on the right. For all these specimens the photographs were taken with the flash mode of the camera on since this tended to best highlight the damage. It should be noted that in practice the amount of visual damage in the field will vary depending upon such factors as the available lighting, the angle of the lighting and the surface finish of the specimen.

For the lower levels of impact energy, the damage is more noticeable on the honeycomb core specimens for any given impact energy. This is due to the ductile aluminum honeycomb ‘holding’ the dent better than the foam which, when damaged, tends to ‘spring back’ masking the severity of the impact event. This was evident in the previous study¹ in which foam core specimens needed to be hit at a higher impact energy level than honeycomb core specimens to produce barely visible impact damage (BVID). Once face sheet perforation is reached ($\approx 8 \text{ ft}\cdot\text{lb}$ in this study), then the damage is equally noticeable on both types of specimens.

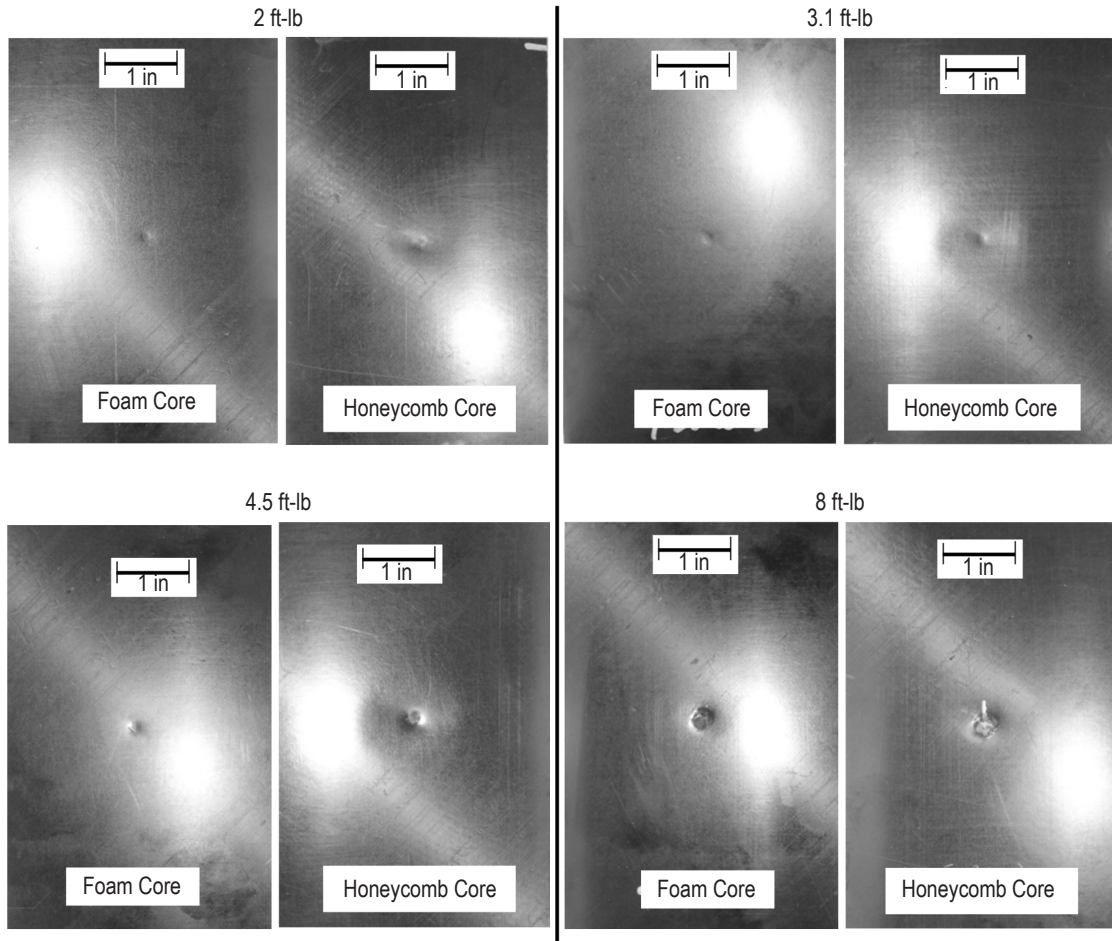


Figure 4. Photographs of various impacts with a 0.5-in impactor on foam core and honeycomb core sandwich structure.

The amount of internal damage to each specimen was determined by flash thermography. Flash thermography signatures of each of the damage zones from the four impact severity levels are shown in figure 5. The foam core specimens are on the left and the honeycomb specimens are on the right.

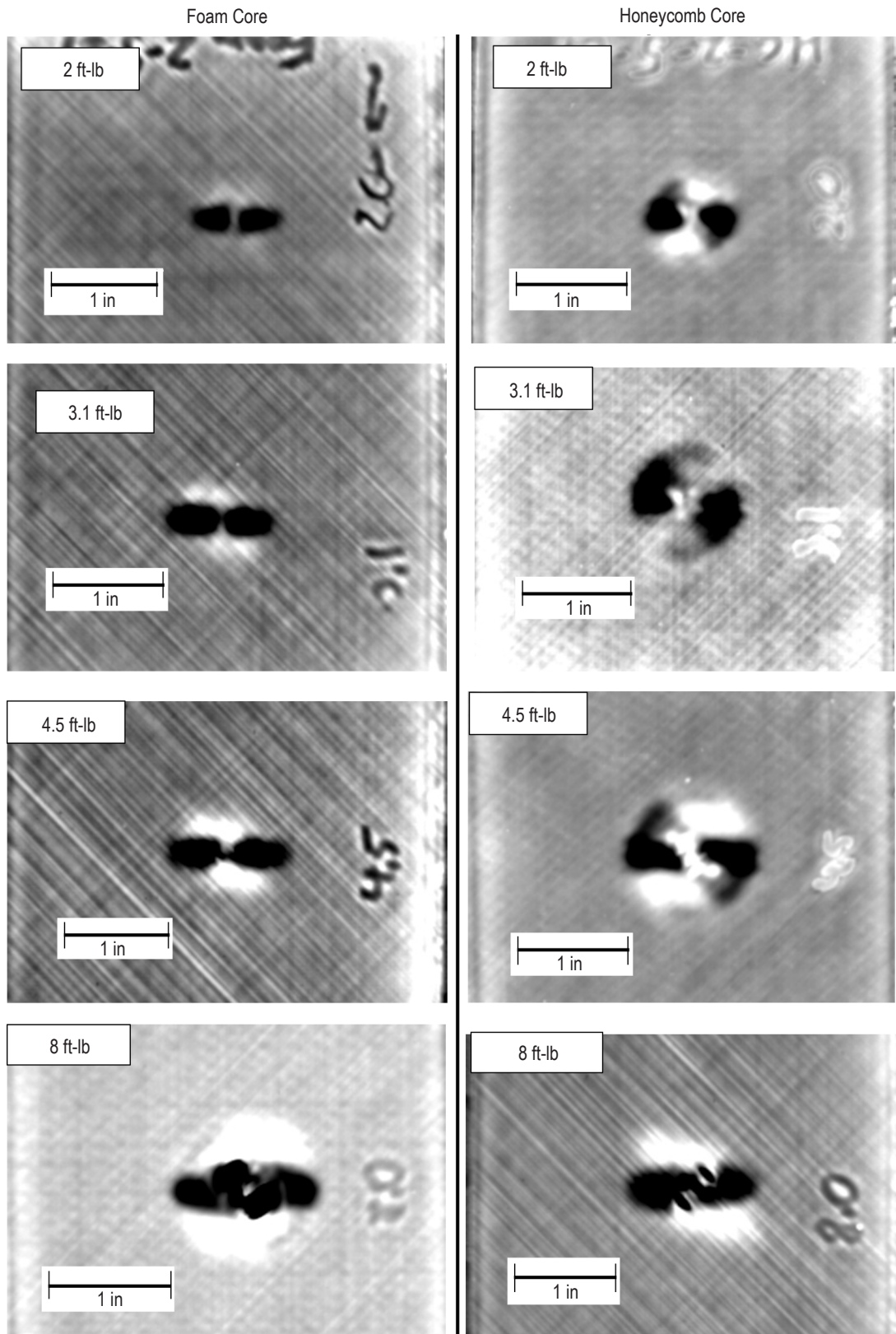


Figure 5. Flash thermography of damage for the samples tested in this study.

Samples from each of the four impact severity levels tested were cross-sectioned thru the impact zone in the width (90°-direction) and photographs taken of the damage. These results are presented in figure 6.

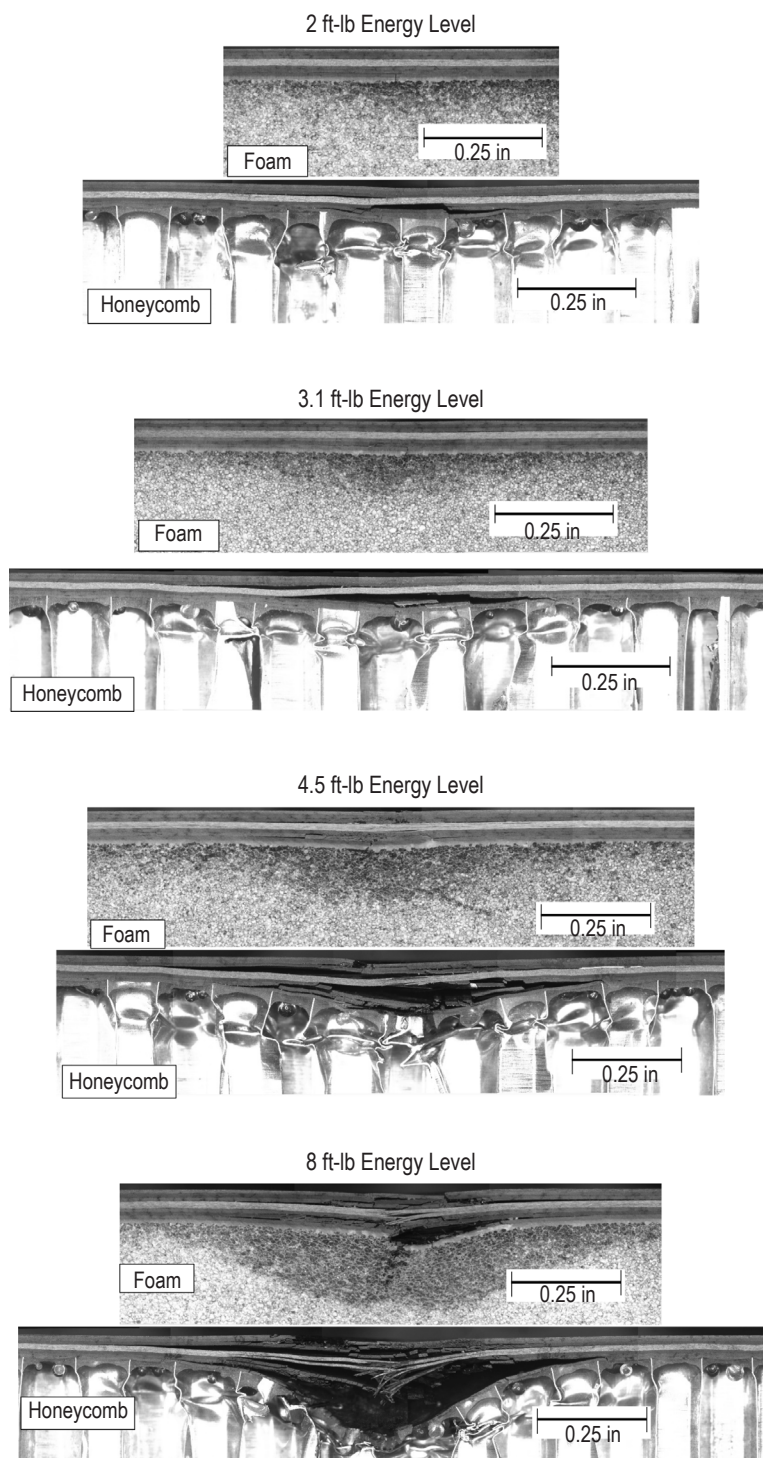


Figure 6. Cross-sectional pictures of damage due to each impact energy level tested for the specimens used in this study.

For any given impact energy, it appears that the face sheet on the honeycomb core specimens experience more damage than the face sheets on the foam core specimens which corresponds to the flash thermography results.

A sample of the load-deflection curves of the impact event produced by each of the various levels of impact energy are shown in figure 7. These results were taken from the instrumented impact tester used. The honeycomb core specimen results are shown in black, and the foam core specimen results are shown in blue.

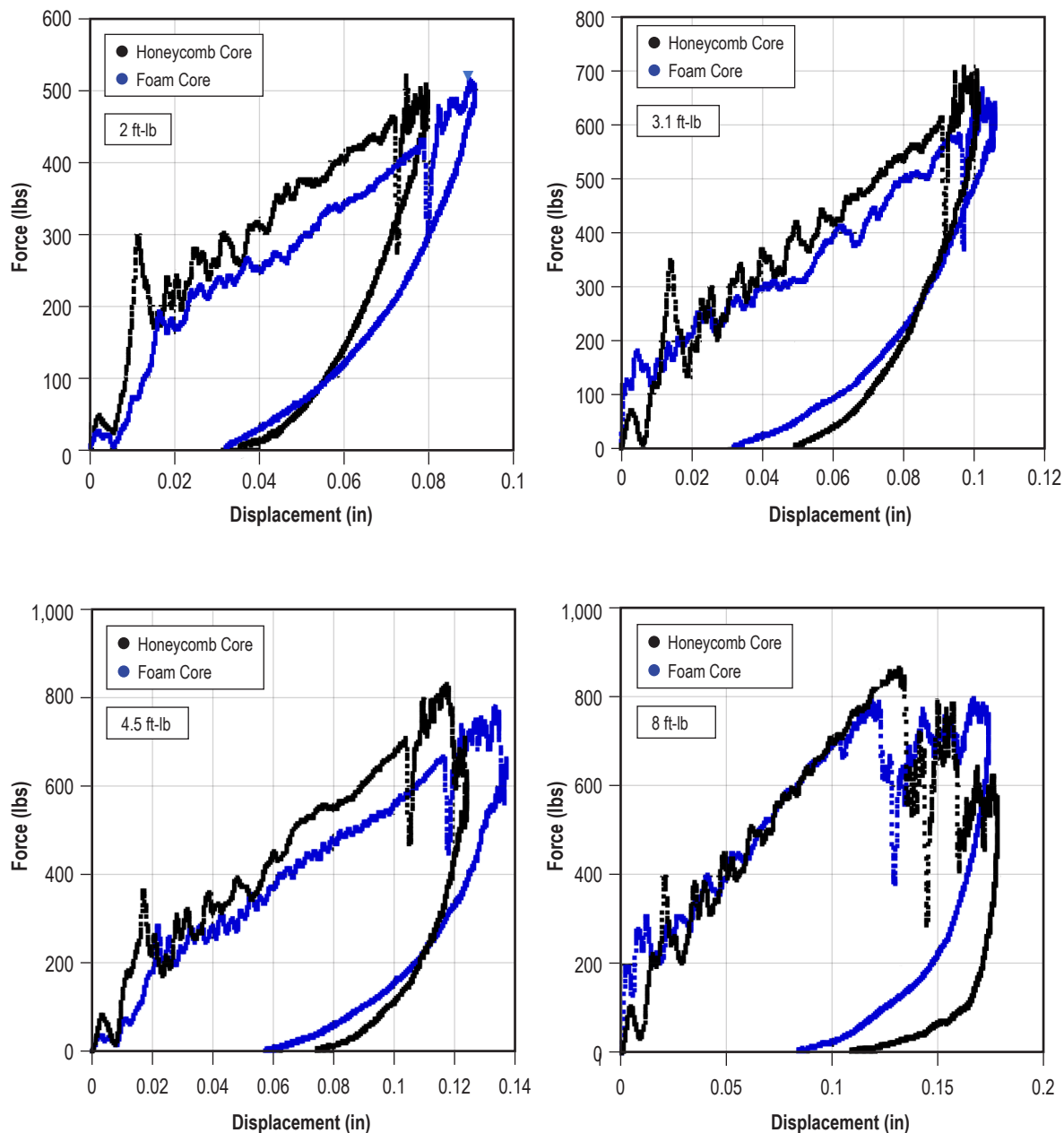


Figure 7. Load-deflection curves for the impact event for the four impact energy levels tested.

The load-deflection plots in figure 7 appear not to vary greatly between the honeycomb core and foam core sandwich specimens. In general, the aluminum honeycomb core specimens showed a slightly higher maximum load of impact than foam core specimens hit with the same impact energy. This is probably due to the foam core having a lower compressive modulus and strength, although the magnitude of the difference in these maximum loads are not proportional to the much lower compression modulus and strength of the foam core. Results that show a modest increase in maximum load of impact at any given impact energy although one core may have a much higher compression strength and modulus has been noted elsewhere.^{2,3}

4. COMPRESSION AFTER IMPACT TESTING

The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 8. The loading was in the 0° fiber direction (core oriented in the W-direction). Three strain gages were placed on the specimen as diagramed in figure 9 to ensure even loading of each of the face sheets. The specimens were taken to approximately 2,000 microstrain, and if one gage was lower than the others by more than 10%, shims were placed under the edge that was reading low until the gages were even. During compression testing, the gages were monitored and if any deviation greater than 10% occurred, the test was stopped, and shims would be rearranged until the gages read within 10% of each other all the way until failure of the specimen.

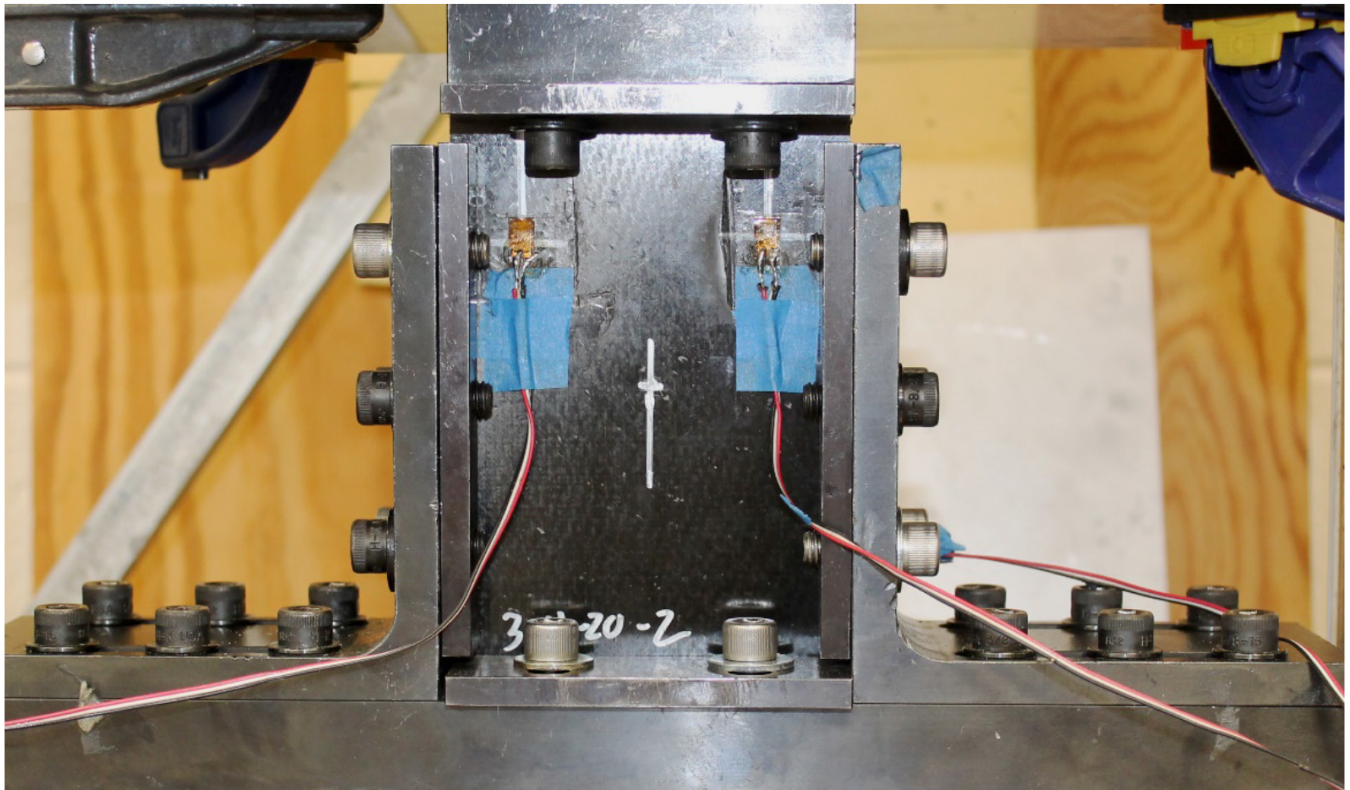


Figure 8. Photograph of fixture used for assessing CAI strength of sandwich specimens

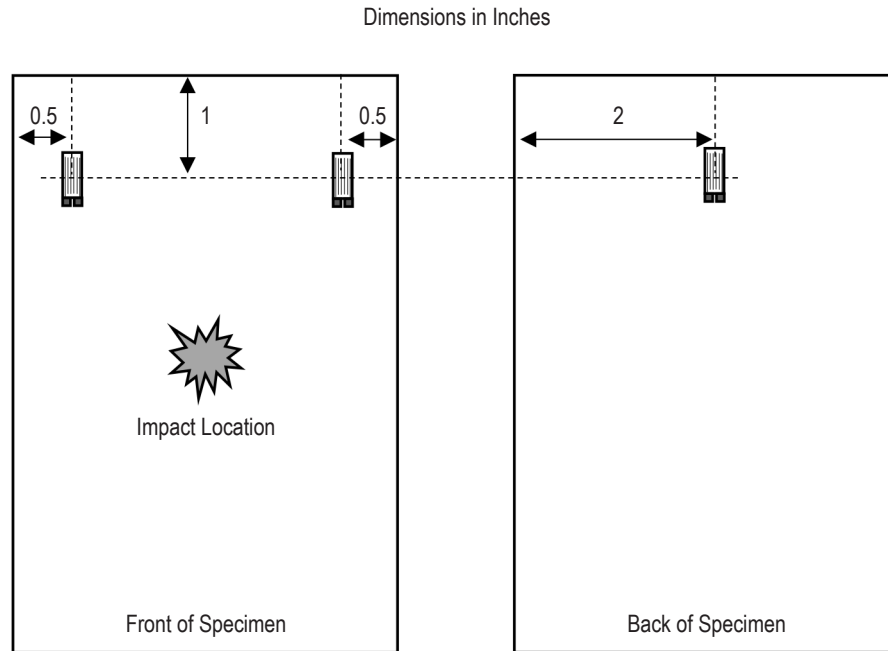


Figure 9. Location of strain gages on front and back of each CAI specimen

The CAI strength results are shown in table 4 using line load (load divided by specimen width) at failure. Figure 10 shows these results graphically.

Table 4. Summary of results from CAI testing.

Core Type	Impact Energy (ft-lb)	CAI Strength (lbf/in)
Foam	2.02	5,156
	2.02	5,032
	2.02	4,995
	2.01	4,897
	1.89	4,869
	3.11	4,418
	3.11	4,524
	3.11	4,452
	4.58	4,451
	4.59	4,378
	4.59	4,307
	7.66	3,850
	7.52	3,841
	7.79	3,972

Table 4. Summary of results from CAI testing (Continued).

Core Type	Impact Energy (ft-lb)	CAI Strength (lbf/in)
Honeycomb	1.97	4,646
	1.98	4,752
	2.04	4,374
	3.12	4,169
	3.12	5,104
	3.12	4,033
	4.55	3,915
	4.56	3,641
	4.58	3,733
	7.96	3,372
	8.02	3,436
	7.98	3,727

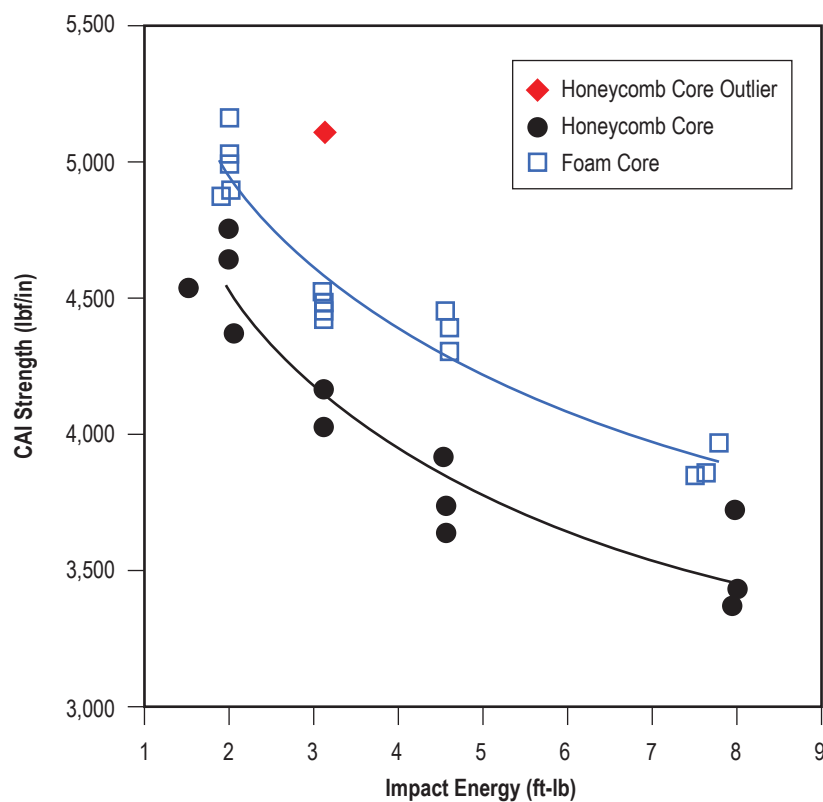


Figure 10. Plot of CAI data for specimens tested thus far in this study.

Note that there is an obvious outlier in the honeycomb core specimen data at the 3.1 ft•lb impact severity level (denoted by a red diamond symbol). This measured CAI strength is unusually high. This specimen did differ from all others in that it experienced two loading cycles to over

70% of ultimate since the strain gages began to diverge from greater than 10% of each other. This was the only CAI test that was stopped once the gages were first balanced at the 2,000 microstrain level. It has been noted by the author that CAI sandwich specimens that experience high-level load cycles before taken to failure tend to fail at a higher static load than equivalent sandwich structure that has not first experienced excursions to a high load.⁴ Ignoring this outlier, a power curve has been fit through the data for each type of core specimen, and it is clear that the foam specimens have a higher CAI strength for any given impact severity level. The phenomenon of increased CAI strength after high level load excursions is being further investigated in a follow-on study.

These results were surprising since the honeycomb core specimens had been expected to have a considerably higher CAI strength for a given impact energy based on the results in the previous study. It was observed that the CAI failures of the foam core specimens were mostly in the core with occasional face sheet damage seen near the edges of the specimen either on the front or the back of the specimen. The CAI failures of the honeycomb specimens were always in the impacted face sheet with the failure zone running perpendicularly through the impact damage zone. These results were identical to the results in the previous study¹ and were not unexpected based on the low properties of the foam core. Examples of these types of failures are shown in figure 11 which are specimens that were impacted with 8 ft•lbf of energy. Figure 12 shows the foam core of the specimen in figure 11 after removal of the face sheets. It can be seen that the core failed as a ‘shear plug.’

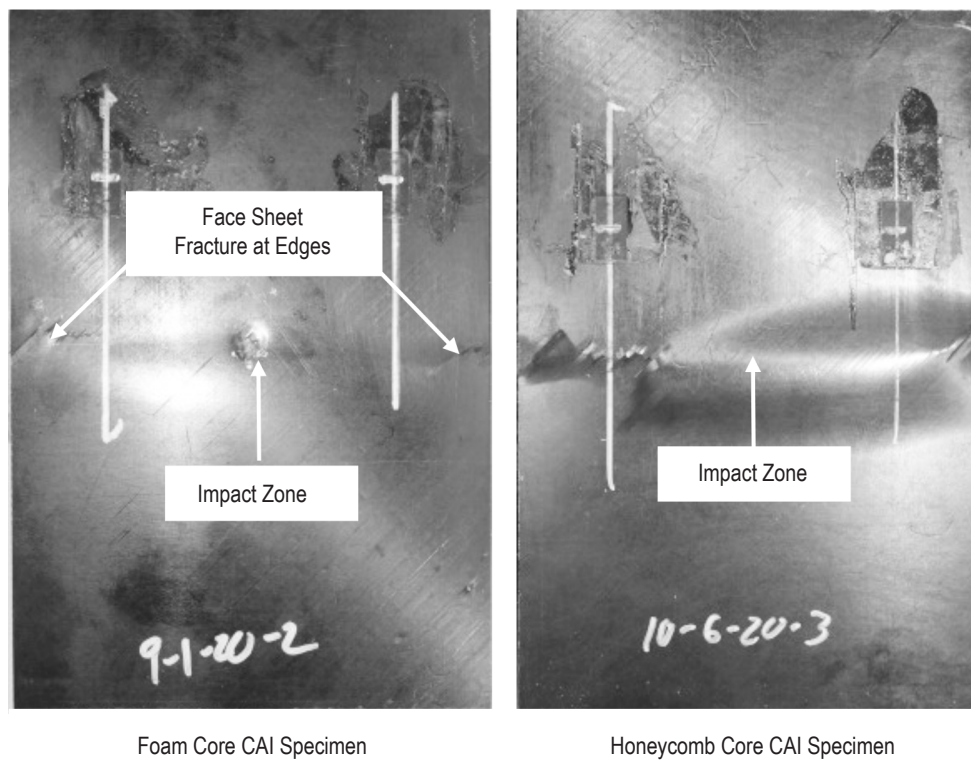


Figure 11. Photographs of post failure CAI specimens with foam core (left) and honeycomb core (right).

The impacted face sheet from the specimen in figures 11 and 12 was removed and examined from the inner (core side) surface to show that it did not fail at the impact damage zone. A number of foam core specimens had their face sheets removed, and the failure was always by core shear (as seen in figure 12) with no damage emanating from the impact zone of the face sheet as shown in figure 13.

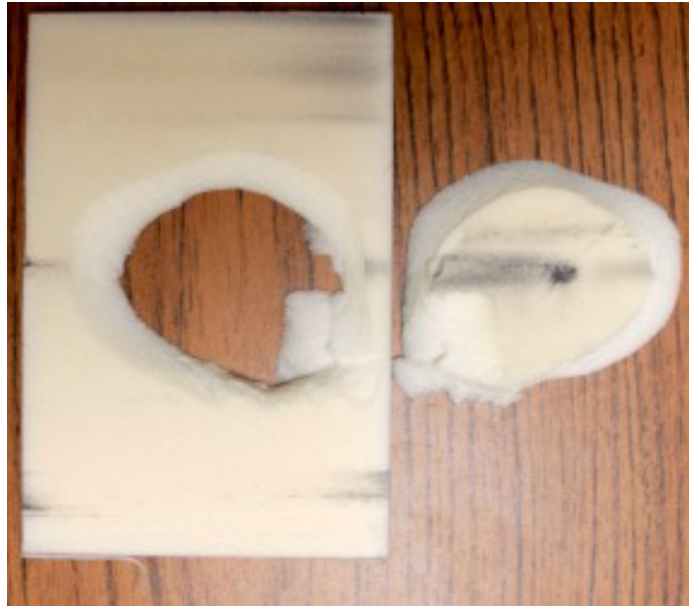


Figure 12. Photograph of core of foam specimen in figure 11 showing that the core failed in shear.

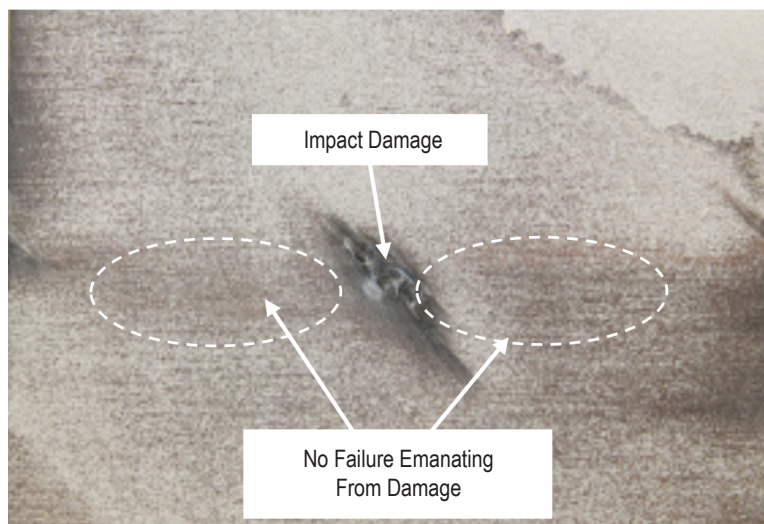


Figure 13. Photograph of core side of face sheet at impact damage on specimen in figures 11 and 12 to show that failure did not initiate from the impact damage in the face sheet.

The main difference in the honeycomb specimens in this study versus the specimens in the previous study¹ were that the core was oriented with the W-direction in the direction of loading in this study and oriented in the L-direction in the previous study.¹ Since face sheet failure was the governing failure mechanism for the honeycomb core specimens in both this study and in the previous study,¹ it was thought that the CAI strength results should be similar since the core should not come into play if face sheet failure occurs. The damage width formed due to the impact event was no different since in figure 4, it can be seen that the damage area is circular and thus a 90° rotation would not affect the width of damage on the specimens which has been shown to be the best governing factor to determine CAI strength of sandwich structure.⁵

To ascertain if the W-direction being in the loading direction of the specimens was indeed responsible for the low CAI strength values, a series of CAI tests were undertaken rotating the specimens in this study by 90° such that the core L-direction was now aligned with the loading direction. This meant that the face sheets now had an orientation of $[+45/90/-45/0]_s$ rather than $[-45/0/+45/90]_s$. This change in orientation of the face sheet was not expected to greatly affect the CAI strength results. Compression testing of carbon fiber laminates has been shown to give similar strength values for a given percentage of 0° plies except when the load bearing 0° plies are on the outer surface of the laminate in which case the measured compression strength values will be lower.⁶ The impact results of the 90° rotated honeycomb sandwich specimens are given in table 5 and the CAI results are given in table 6. These results are plotted graphically in figure 14.

Table 5. Summary of results from impact testing of honeycomb specimens rotated 90°.

Configuration	Impact Energy (ft-lb)	Specimens Tested	Maximum Load of Impact (lb)	Dent Depth (mil)
Honeycomb Core L-direction	2.0	1	563	10.5
	3.1	4	703±11	15.0±1.0
	4.5	3	843±16	25.8±6.0
	8.0	2	852±28	52.3±1.8

Table 6. Summary of results from CAI testing of honeycomb core in the L-direction.

Core Type Honeycomb L-Direction	Impact Energy (ft-lb)	CAI Strength (lbf/in)
	2.02	6,128
	3.11	5,314
	3.11	4,745
	3.10	5,241
	3.10	5,160
	4.51	4,943
	4.51	4,957
	4.54	4,278
	7.87	3,881
	7.88	3,872

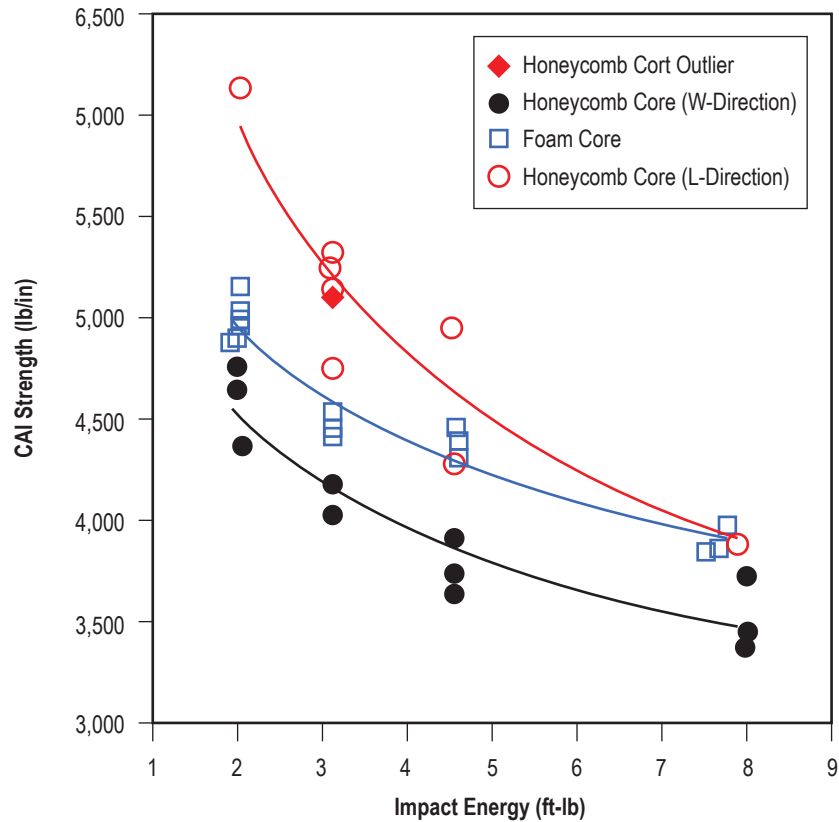


Figure 14. Plot of CAI data for all specimens in this study.

These results show that rotating the honeycomb core specimens 90° so that the loading was in the L-direction gave higher CAI strength values, especially at the lower impact severity levels. The reason(s) for this are not clear, and more experimentation is needed to draw conclusions, namely testing honeycomb core with the loading direction in both the L-and W-directions and with the exact same face sheet orientation since the face sheets in this test program were rotated by 90° when the core was switched from loading in the W-direction to loading in the L-direction. For completeness, a photograph of a failed specimen tested in the L-direction is shown in figure 15. All failures on these specimens were in the face sheet through the damages zone.

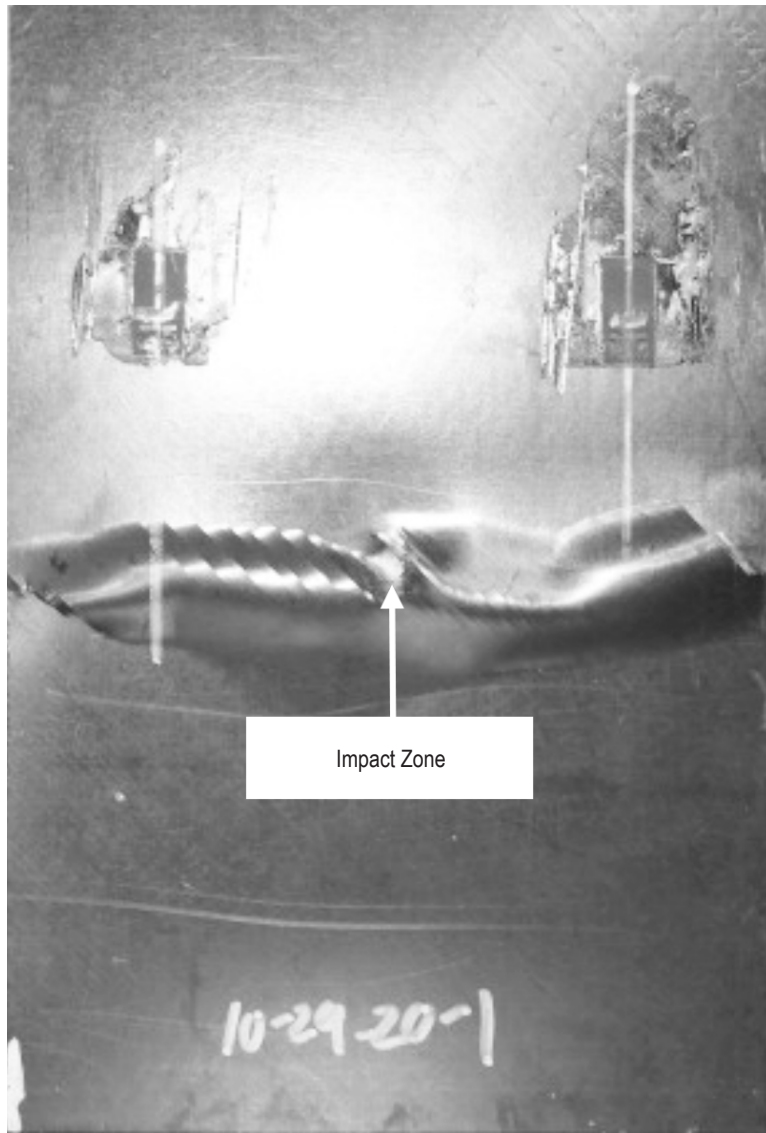


Figure 15. Photographs of post failure CAI specimen that was tested with the honeycomb with the L-direction in the direction of loading.

5. NORMALIZING BY WEIGHT

Since low mass is such a critical parameter for space launch vehicle applications, a comparison of the CAI results of the foam core and honeycomb core specimens can be examined when mass is considered. In order for the normalized strength numbers to make more physical sense, the areal density values in table 2 are multiplied by the area of each specimen (24 in²). This gives the weight of each specimen in lbm. The results are:

- Foam core specimen = 0.206 lbm.
- 1-in-thick honeycomb specimen = 0.240 lbm.
- 0.5-inch-thick honeycomb specimen = 0.178 lbm (calculated).

The weight of each type of specimen can be divided into the CAI strength values to give a CAI strength value per pound weight of each of the two types of core tested and the inferred normalized CAI strength of 0.5-inch-thick aluminum honeycomb sandwich structure. These normalized CAI strength results are presented in table 7. These results are also plotted in figure 16 with a power curve fit for each of the type of specimens presented.

Table 7. Summary of weight normalized results from CAI testing.

Core Type	Impact Energy (ft-lb)	CAI Strength (lb/in)/lb _m
Foam	2.02	25,029
	2.02	24,427
	2.02	24,247
	2.01	23,772
	1.89	23,636
	3.11	21,447
	3.11	21,961
	3.11	21,612
	4.58	21,607
	4.59	21,252
	4.59	20,908
	7.66	18,689
	7.52	18,646
	7.79	19,282
Honeycomb (1 in Thick Loaded in the W-Direction)	1.97	19,358
	1.98	19,800
	2.04	18,225
	3.12	17,371

Table 7. Summary of weight normalized results from CAI testing (Continued).

Core Type	Impact Energy (ft-lb)	CAI Strength (lb/in)/lb _m
Honeycomb (1 in Thick Loaded in the W-Direction Continued)	3.12	21,267
	3.12	16,804
	4.55	16,313
	4.56	15,171
	4.58	15,554
	7.96	14,050
	8.02	14,317
	7.98	15,525
Honeycomb (0.5 in Thick Loaded in the W-Direction)	1.97	26,101
	1.98	26,697
	2.04	24,573
	3.12	23,421
	3.12	28,674
	3.12	22,657
	4.55	21,994
	4.56	20,455
	4.58	20,972
	7.96	18,944
	8.02	19,303
	7.98	20,938
Honeycomb (1 in Thick Loaded in the L-Direction)	2.02	25,533
	3.11	22,142
	3.11	19,771
	3.10	21,838
	3.10	21,500
	4.51	20,596
	4.51	20,654
	4.54	17,825
	7.87	16,171
	7.88	16,133
Honeycomb (0.5 in Thick Loaded in the W-Direction)	2.02	34,427
	3.11	29,854
	3.11	26,657
	3.10	29,444
	3.10	28,989
	4.51	27,770
	4.51	27,848
	4.54	24,034
	7.87	21,803
	7.88	21,753

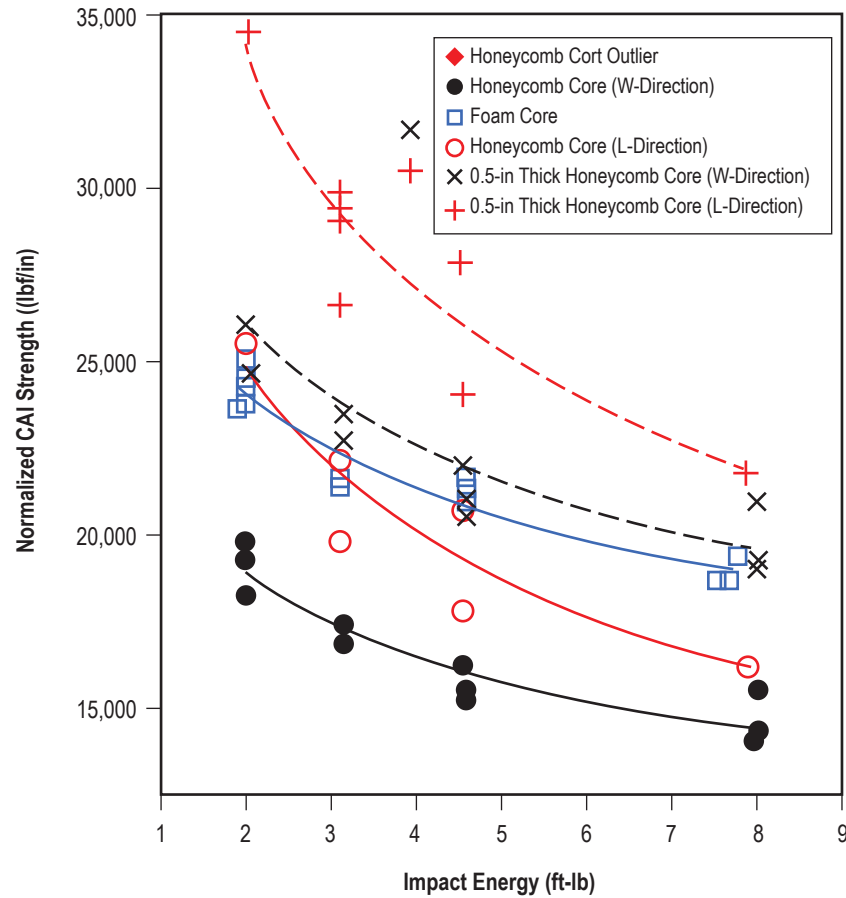


Figure 16. Plot of weight normalized CAI data for all specimens in this study.

When normalized by weight, 0.5-in-thick honeycomb loaded in the L-direction should give superior CAI strength values compared to the foam core specimens. If 1-in-thick honeycomb core is compared to 0.5-in-thick foam core, then the foam core specimens have a higher specific CAI strength even when the honeycomb core is aligned in the L-direction.

6. CONCLUSIONS

Some of the conclusions that can be drawn from this study are:

- For a given impact energy level, the dent depth is deeper on the honeycomb core sandwich specimens, which is beneficial if visible damage is being used as a criterion.
- When honeycomb core sandwich structure was loaded in the W-direction, the foam core sandwich specimens had a higher CAI strength for a given impact energy, but when oriented in the L-direction, the honeycomb core specimens had a higher CAI strength. The reason for this is unknown to the author and is being investigated further.
- As the impact energy increases, the difference in CAI strength becomes less for the specimens tested in this study.
- When normalized by weight the 0.5-in-thick foam core specimens gave higher CAI strength values, especially at higher impact energy levels, than the 1-in-thick aluminum honeycomb core specimens even when the 1-in-thick honeycomb core specimens were tested in the L-direction.
- If 0.5-in-thick aluminum honeycomb had been used, it is predicted that these specimens would give much higher CAI strength values when compared on a weight basis when tested with the core in the L-direction. With the core in the W-direction, the weight normalized CAI strength values would have been similar to the foam core specimens.

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14. ABSTRACT This Technical Memorandum is a follow-on study to a previous one ¹ that examined the compression after impact (CAI) strength of carbon fiber sandwich structure with aluminum honeycomb core and Rohacell foam core with barely visible impact damage (BVID). In this current study a wider range of impact energies were utilized and the CAI strength assessed with these different damage severity levels. This was done to provide a more complete database for the two types of sandwich structure tested in these studies. In addition, the honeycomb sandwich specimens were tested with both the 'L' and 'W' directions aligned with the axis of compression loading. As in the study examining CAI strength with BVID ¹ , the results were normalized by the mass of the sandwich structure. The results showed that the CAI strength did differ depending on the orientation of the core during testing and that when tested in the W-direction, the honeycomb core sandwich structure had about the same CAI strength as the foam core sandwich structure when normalized by the mass of the sandwich structures.					
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